International Journal of Disaster Risk Reduction 50 (2020) 101861

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: http://www.elsevier.com/locate/ijdrr

Developing a comprehensive methodology for evaluating economic impacts of floods in Canada, Mexico and the United States

Zafar Adeel [a,*], Ana María Alarcón [b], Laura Bakkensen [c], Ernesto Franco [d], Gregg M. Garfin [e], Renee A. McPherson [f], Karla Méndez [d], Marie Blanche Roudaut [e], Hirmand Saffari [a], Xin Wen [a]

[a] *Pacific Water Research Centre, Simon Fraser University, Canada*
[b] *Universidad Nacional Autónoma de México, Mexico City, Mexico*
[c] *School of Government & Public Policy, University of Arizona, Tucson, AZ, USA*
[d] *Centro Nacional de Prevención de Desastres, Mexico City, Mexico*
[e] *School of Natural Resources and the Environment, University of Arizona, Tucson, AZ, USA*
[f] *South Central Climate Adaptation Science Center & Department of Geography and Environmental Sustainability, University of Oklahoma, Norman, OK, USA*

ARTICLE INFO

Keywords:
Floods
Comprehensive economic impacts
Flood damages and losses
Post-disaster reconstruction

ABSTRACT

Assessing the true economic costs of floods is central to addressing their impacts, allocating adequate resources for monitoring and preparedness, assessing their changes over time, and building resilient communities. Considerable variability exists in the choice and implementation of methods used in Canada, Mexico, and the United States at national and sub-national levels for estimating the direct damages and indirect losses caused by floods. This inter- and intra-national variability leads to information gaps when prioritizing development investments, for example, for infrastructure renewal, institutional development, or community enhancements. This paper provides an overview of the range of approaches used in the three countries and analyzes their strengths and weaknesses. It then presents a proposed comprehensive and inclusive methodology that has been developed in close collaboration with a range of stakeholders and domain experts. This methodology builds on existing approaches and offers a comprehensive accounting of costs related to flooding. We offer insights into potential challenges for implementing this methodology across the three countries, particularly related to data availability, access, quality, and spatial coverage. We recommend enhanced gathering data and metadata, and storing it in an information warehouse for their timely dissemination. We also identify the need for further investigation into the definition for "extreme flooding" that incorporates hydrological, societal and economic thresholds, in collaboration between government agencies and the research community.

1. Introduction

Flooding, including in-land and coastal flooding, is one of the most devastating and costly natural hazards in North America [1–3]. Because of increased population and more exposed assets in hazard-prone areas, more devastating and costly flooding are expected in the future. Changes in climate patterns are likely to exacerbate this trend, bringing heavier rainfall events, sea level rise, increased flooding from more intense hurricanes, and coastal erosion [4–6]. Importantly, flood events across the international borders between Canada, Mexico, and the United States have led to significant economic impacts and loss of human life in recent years [7]. For example, the 1997, 2009, and 2011 Red River floods cumulatively resulted in billions of dollars of damage in Manitoba (Canada) and North Dakota and Minnesota (the United States). Similarly, in the Rio Grande/Rio Bravo watershed, communities along the United States-Mexico border continue to face serious flood events [8]. Inadequate collaborations and agreements between the United States and Mexico prevented joint action towards a binational flood control plan for many years [7], creating severe flood-related economic impacts during the early and mid-twentieth century.

Likewise, historical extreme flooding in the Columbia River in 1948 catalyzed the formulation of the Columbia River Treaty (CRT) between Canada and the United States, entered into force in 1964, and subsequently led to the construction of three major dams for flood-control purposes [9,10]. The CRT stipulated that the United States had to pay Canada for the construction of these dams and shared benefits from

* Corresponding author. Simon Fraser University, Technology and Sciences Complex 1, Room 8405, 8888 University Drive, Burnaby, BC, V5A 1S6, Canada.
E-mail address: zadeel@sfu.ca (Z. Adeel).

https://doi.org/10.1016/j.ijdrr.2020.101861
Received 22 May 2020; Received in revised form 25 August 2020; Accepted 8 September 2020
Available online 14 September 2020

hydropower generation in the United States. As the CRT approaches its 60-year tenure, negotiations are ongoing between the two countries to accommodate major transitions in energy demands, hydrologic alterations as a result of climate change, viability of aquatic ecosystems and species, empowerment of Indigenous communities, and continued flood protection [10,11]. The comprehensive valuation of flood-related economic impacts, therefore, remains relevant in deciding the future of this treaty.

Overall, to improve disaster prevention, emergency responses, and recovery strategies, however, it is first necessary to better understand the consequences of floods on local and regional economies, and to develop methodologies to estimate the comprehensive cost of such disasters [12]. At present, the methods by which costs of flood damages are estimated vary significantly among federal and state or provincial jurisdictions across Canada, Mexico, and the United States, resulting in widely different quantification of these costs [3,13–18].

In the United States, governmental agencies are assigned to collect information on the economic impacts of extreme events at national and sub-national levels – for example, physical damage to residential, commercial, and public buildings; loss of time and productivity; damage to vehicles, offshore energy platforms, and public infrastructure; agricultural assets (crops, livestock, and timber); and disaster restoration and wildfire suppression costs [19]. In Canada, Public Safety Canada administers the Disaster Financial Assistance Arrangements whose regional offices assist with damage assessments, interpretation of guidelines, and surveillance of private damage claims [20]. In Mexico, the Centro Nacional de Prevención de Desastres (CENAPRED) collects information from the public and private sectors and estimates the cost of damages from natural and human-induced hazards, including flood and droughts [13]. Not only are there considerable differences at the national level but also across the three countries in harmonizing and integrating the pertinent economic impact information over both space and time. There also are significant data gaps in uninsured economic impacts of flooding [12,21]. These information gaps limit joint responses between Canada, Mexico, and the United States, particularly when encountering extreme events that impact multiple jurisdictions across international borders. So far there has not been any effort to coordinate these approaches for estimating economic impacts at the multi-national scale [3,22].

Given the aforementioned interconnectivity of extreme weather events in Canada, Mexico, and the United States, particularly in terms of the flooding history, a harmonized tri-national approach for evaluating economic impacts can play an important role in enhancing resilience in at-risk communities and allocation of resources for monitoring. A mutually agreed upon, comprehensive and comparable methodology, when applied across the three countries, would enable systematic investments by the governmental agencies to enhance resilience to extreme floods, reduce the economic impact of future events, and support real-time monitoring and disaster response. A common cost-assessment methodology also would enable regional collaboration in applied and targeted research on future impacts of extreme events, operations for mitigating impacts of extreme events, analysis of social disparities in flood costs and relief efforts, and coordinated policy-making among the three countries. It also would allow tracking of costs over time and space for analysis of trends and research on interconnections among events.

The Commission for Environmental Cooperation[1] (CEC), an organization created by the governments of Canada, Mexico, and the United States, recognized information gaps in estimating economic impacts of floods and has initiated in 2019 a collaborative research project in response. This project entitled "Costing Floods and Other Extreme Events" brings together governmental agencies, academic institutions, and stakeholders from the private sector and communities. The work presented in this paper is based on an expert dialogue between the project's collaborators and includes the assessment of existing approaches in the three countries.

2. Methods

2.1. Scope of the paper

The content of this paper is drawn from the desk-based study undertaken by the CEC project team based in Canada, Mexico, and the United States. The scope of the CEC project, and of this paper, is limited to the economic impacts triggered by flooding – including direct damages to property and infrastructure and indirect losses triggered by disruption of routine activities and economic flows. The project design duly recognized that loss of life, acute and chronic health impacts, and psychological and social disruptions are also critically important [23]. However, inclusion of these broad social, non-economic considerations was deemed to be outside the scope of the limited available time and financial resources for the implementation of the project. Non-economic impacts of flooding that affect Indigenous communities are part of the CEC project but outside the scope of this manuscript.

This analysis was supported by the First CEC Expert Workshop that took place in Vancouver in September 2019. That workshop brought together government and academic experts, researchers, and representatives from the insurance industry and related planning organizations from Canada, Mexico, and the United States. This paper presents both the analyses of existing methods used in the three countries and the proposed methodology developed through the dialogue conducted at the expert workshop and extensive subsequent consultations. Proof-of-concept application of this methodology to the flood-related economic impacts in the three countries is part of the team's ongoing research and is outside the scope of this paper.

2.2. Analytical approach used

First, we conducted a systematic review of the methods used to evaluate the economic impacts of floods in Canada, Mexico, and the United States. In the early review process, we defined search keywords and conducted a Title & Abstract search. Data collection consisted of a search of electronic literature databases to identify sources, including peer-reviewed articles, grey literature (e.g., government reports, policy statements, and issue papers), and books. Then, we conducted a full text screening to identify publications that met one or more of the following criteria:

- Criterion 1: The studies had to focus on the economic damages and indirect losses caused by floods in Canada, Mexico, and the United States. (Studies that did not include economic impacts were not considered further.)
- Criterion 2: The publications evaluated governmental approaches for assessing economic impacts of floods.
- Criterion 3: The publications evaluated the approaches for economic assessment and risk analysis used by the insurance sector.

In Canada, the flood-costing methods were assessed through an analysis of recent peer-reviewed publications, and government and insurance sector reports. Information on challenges in measuring flood impacts, approaches used for overcoming those challenges, and gaps in data collection approaches was analyzed. Case studies that highlight the effectiveness, challenges encountered, and limitations of applying flood-costing methodologies in various Canadian cities were a central element

[1] The Commission for Environmental Cooperation – established in 1994 through the North American Agreement on Environmental Cooperation – facilitates collaboration and public participation to foster conservation, protection and enhancement of the North American environment for the benefit of present and future generations, in the context of increasing economic, trade, and social links among Canada, Mexico, and the United States.

of the literature review. The academic literature on existing flood-costing methodologies in Canada was found to be vast and interdisciplinary. Information on these methods was found in disaster management, water resources, and economic policy journals. Open-access data and information from national government agencies such as the Office of the Parliamentary Budget Officer, Public Safety Canada, and Statistics Canada were also reviewed. Private-sector information found in many reports published by the Insurance Bureau of Canada (IBC) and Swiss Re was also considered. Three key flood-costing methodologies used in Canada were identified that have been accepted by government, industry (notably, the insurance sector), and researchers to varying degrees.

In Mexico, the review focused on the CENAPRED annual report, namely "Socioeconomic Impact of the Major Disasters Occurring in the Mexican Republic". The United Nations Economic Commission for Latin America and the Caribbean (referred to as ECLAC hereafter) method is used to estimate the economic and social impact of disasters, especially rains, floods, tropical cyclones, and other phenomena [24]. The ECLAC method is used in Mexico to determine the economic impacts of floods in various sectors, as estimated by the government agencies responsible for each sector [25]. A contribution of CENAPRED to the ECLAC method was the inclusion of data on the costs of emergency care, starting in 2004 [25]. Moreover, the CENAPRED has established a homologous database. It was possible to note that the impacts of meteorological phenomena represent the greatest damages and losses in Mexico from 1999 to 2019 [26].

For the United States, the review focused on flood damage assessment methods that are used by federal and state government agencies and the private sector. The review was focused on direct damages to property and infrastructure and indirect losses triggered by disruption of routine activities and economic flows. At the same time, we recognized that mortality and morbidity as well as other social impacts (e.g., loss of structured education, stress on families) are also important, yet beyond the scope of our review. The flood costing methodologies were summarized through a review of academic publications, government manuscripts, and the insurance sector reports. There are a wide variety of methods used in the United States by various government agencies and the private sector. For the purpose of clarity, they have been divided into the following categories: 1) aggregation of human assessment/insurance loss data; 2) model-based methods; 3) selected Federal budgetary outlays; and 4) selected State, Local, and Tribal government budgetary outlays.

Second, this paper is a follow-up to the First CEC Expert Workshop that took place in Vancouver in September 2019 and comprised representatives of the academic, governmental, and private sectors. The panel of experts contributed the following expertise:

- Appropriate scientific qualifications and research experience in natural hazard assessment.
- A record of peer-reviewed publications on natural hazard assessment, mitigation, and management.
- High-level experience in the design and management of global, regional, or national assessments relating to natural hazards.

In this two-day workshop, 22 organizational representatives from the three countries discussed the proposed methodology for costing of flood damages in Canada, Mexico, and the United States, particularly highlighting its strengths and weaknesses. The *modus operandi* of the workshop was based on open, candid dialogue and blue-sky thinking, which led to productive and free-flowing discussions. The objective of this workshop was to review and fine-tune the proposed methodology by discussing its strengths and weaknesses. In this workshop, the participants critically reviewed the existing methods used in the three countries and offered their perspectives on challenges, opportunities, and possible directions for the CEC project. These perspectives respectively included those from the various agencies in the three federal governments, researchers and experts in flood-related risk management, and insurance-sector representatives. The workshop participants also offered specific guidance related to development of a comprehensive tri-national methodology. The overall approach for formulating the workshop recommendations was based on consensus development through exploration of diverse perspectives. In particular, perspectives from the insurance sector were important in formulating language and terminology which is in sync with the industry standards.

3. Results

Assessing the economic impact of floods is a complex process that requires uniform guidelines for collecting, evaluating, and reporting pertinent information. The costs of direct impacts are generally easier to quantify than indirect costs. Indirect impacts, termed losses in the context of this paper, may last for months and even years after a flood event [22]; the prolonged time frame of these losses makes it difficult to document them adequately. Flood impact assessments are performed on different spatial scales, depending on the method used. On a micro-scale, impacts are calculated for each affected object (building, infrastructure, etc.). On a meso-scale, the assessment is based on spatial aggregations such as residential areas or postal zip code, while macro-scale impact estimation typically involves municipalities, regions, and countries [22]. Overall, considerable variability exists in these assessment methods on both micro- and meso-scales across the three countries. We present here a summary of the methods commonly used by each country.

3.1. Methods used in Canada

There are three key flood-costing methods used in Canada that have been accepted by government, industry, and academics to varying degrees. These methods are useful to various levels of government (federal, provincial, and municipal), have common features and key differences among them, and comprise specific approaches for data collection, analysis, and presentation which are discussed in subsequent sections. The findings from these flood-costing methodologies are presented through output-generated models, simulations, graphs, and tabular presentation of data. The quality, composition, and accuracy of these outputs are broadly dependent on the input data quality [17].

3.1.1. Federal Assistance Programs

The Office of the Parliamentary Budget Officer (PBO) estimated the average annual cost of the Disaster Financial Assistance Arrangements (DFAA) program over the next five years (2016–2020) due to extreme weather events [27]. Data for estimated future insured losses due to hurricanes, convective storms, and winter storms are obtained from Risk Management Solutions Inc.[2] (RMS), and the future flood residential property loss data are obtained from the IBC. The estimate of future flood losses by IBC is then increased to include total commercial and public infrastructure losses, using the proportion of public sector and commercial fixed assets measured by Statistics Canada [27]. For example, the categories of health care and social assistance, educational services, and government sector are included in public infrastructure. The DFAA payment for flood-related costs on an annual basis is then calculated as a fraction of total losses, based on the historic estimates of the ratio between uninsured economic impacts and total losses over a ten-year period (2005–2014) [27].

As a related effort, Public Safety Canada maintains the Canadian Disaster Database (CDD)[3] which contains disaster related information —

[2] Risk Management Solutions Inc. (RMS) is a catastrophe modeling firm contracted by the Parliamentary Budgetary Office (PBO) to estimate future annual losses for hurricanes, convective storms and winter storms.

[3] https://www.publicsafety.gc.ca/cnt/rsrcs/cndn-dsstr-dtbs/index-en.aspx.

where and when a disaster occurred, the number of injuries, evacuations, and fatalities, and an estimate of the costs — for more than 1000 events that occurred since 1900 that have directly impacted Canadians. It tracks significant disaster events that meet one or more of the following criteria: 10 or more people killed; 100 or more people affected, injured, infected, evacuated, or homeless; an appeal for national/international assistance; historical significance; and, significant damage/interruption of normal processes such that the community affected cannot recover on its own. However, the CDD does not employ a standardized guideline for collecting cost and loss data related to disasters, making it unsuitable for analytical and comparative purposes.

3.1.2. Hazus

Created by the United States Federal Emergency Management Agency (FEMA), Hazus standardizes how public safety agencies assess hazards, including models for estimating potential losses from earthquakes, floods, and hurricanes [28]. It uses Geographic Information Systems (GIS) to estimate physical, economic, and social impacts of disasters. The Hazus model estimates risk by calculating the exposure to a particular hazard (e.g., river flooding) within a selected area and combining that information with the intensity of the hazard's impact on the exposed area, using this information to calculate potential losses [29]. (The Hazus methods are described in greater detail in section 3.3.2). Hazus offers a robust approach to flood loss estimation that is gradually being adopted by governments and organizations worldwide [30].

Though initially developed in the United States, the use of Hazus as a tool to measure the economic impacts of flooding has many practical applications for a variety of Canadian sectors, including insurance, geotechnical engineering, emergency management, and municipal planning [30]. Hazus Canada is a tool that provides municipalities, regional districts, provinces, or consultants with a standards-based approach to various aspects of emergency planning, including planning for mitigation, response, and recovery [30]. Using Hazus Canada, Canadian jurisdictions can also better identify areas at risk from flood hazards that may require changes in land use [30]. There have been many examples of effective application of the Hazus flood model specifically – which includes both coastal and riverine flooding [16,31,32]. The Canadian application of Hazus includes modifications to the built environment by including geographic boundaries used by Census Canada and to the demographic data by using those distributed by Statistics Canada via the Census Program [30]. Nastev and Todorov [31] note that development of consistent strategies for collecting, updating, and maintaining the input inventory and hazard data remains a challenge for Canada. This challenge, among many others related to lack of community participation and education, has prevented widespread uptake of Hazus by the government and industry in Canada.

3.1.3. Computable General Equilibrium (CGE) models

Computable General Equilibrium (CGE) models use a series of equations to summarize market dynamics that are calibrated by empirical economic data to estimate how an economy might respond to changes in policy, technology, or other conditions. CGE models are one of the most utilized tools globally for development planning and macro-policy analysis [33] and evaluating economic impacts of flooding [34]. A dynamic CGE framework for modeling the economic impacts of flooding in Vancouver, British Columbia, was devised in 2015; the underlying purpose of the exercise was to better understand the future severity of damages and losses associated with the increased frequency and intensity of flooding and severe storms as a consequence of anthropogenic climate change [35]. Though damages and losses are typically calculated by totalling insurance claims or surveying flood victims, the loss of economic activity caused by a flood is typically not included in the calculation. Under this CGE framework, the initial damage is modelled as a shock to capital stock, and recovery requires rebuilding that stock. This method accounts for the many economic impacts that occur as a result of flooding, including private consumption, government consumption, disaster financial assistance, investment, imports, exports, taxes, and damages by economic sector – all the while applying these impacts to different potential damage scenarios. The method thus goes beyond the direct economic impacts (such as property and infrastructure damage) and applies a more comprehensive framework to measure the economic impacts of flooding over time [35], yet it has not seen broad uptake in Canada.

3.2. Method used in Mexico

Mexico is one of the few countries in Latin America that keeps a systematic record of the impact of its disasters [36]. Since 1999, CENAPRED has conducted activities aimed at assessing the impact of disasters on the economy and society of the affected regions, as well as their impact on the national economy. The evaluations are presented in an annual book series called "Socio-economic Impact of Disasters in Mexico," with 20 vol [13]. The CENAPRED reports encapsulate the reference database for the social and economic impacts of disasters in Mexico, including floods, based on a methodology endorsed by the United Nations Economic Commission for Latin America and the Caribbean (UN ECLAC) [24]. The ECLAC method is used to quantify the social and economic impacts of disasters and to prioritize the needs that arise in the reconstruction process; it also serves to assess the post-disaster financial needs and prioritize re-construction projects that should be undertaken.

The ECLAC method categorizes economic impacts of disasters such as floods into two broad categories: damages, and losses and additional costs [24]. *Damages* means the monetary impact of floods during the event on the assets of each sector. Depending on the sector, assets may include: (a) Physical assets such as buildings, installations, machinery, equipment, means of transport, storage facilities, furnishings, irrigation systems, dams, road systems and ports; and, (b) Stocks of final and semi-finished goods, raw material, materials and spare parts. Damages are typically measured relative to the baseline or pre-flood situation. *Losses and additional costs* are disruptions to flows resulting from a flood. *Losses* relate to the goods that go unproduced and services that go unprovided during a period running from the time the flood occurs until full recovery and reconstruction is achieved. *Additional costs* are outlays required to produce goods and provide services as a result of the disaster. These represent a response by both the public and the private sectors, which may take the form of additional spending or a re-composition of spending.

In the ECLAC method, direct damages occur at the time of the disaster or within a few hours of its occurrence. In slow-developing events or prolonged processes, such as droughts or El Niño–Southern Oscillation (ENSO) events, direct damages can occur over an extended period and can even multiply if some infrastructure was repaired or replaced at first and later was affected again (e.g., bridges destroyed by repeated floods). From the point of view of the rapid assessment of the damage, it is relatively straightforward to identify and evaluate the direct effects. As far as possible, the starting point for damage estimates should be based on physical units (e.g., number, built-up square meters, hectares, tons, etc.) [24].

Overall, the damages, losses and additional costs are estimated for the following three sectors and the corresponding subsectors [24]:

1. Social sectors:
   - Affected population
   - Education
   - Health
   - Epidemics
   - Housing
   - Culture and cultural assets
2. Infrastructure:
   - Transportation

- Water and sanitation
- Power sector

3. Economic sectors:
   - Agriculture sector (farming, livestock, fisheries, capture fisheries, forests)
   - Manufacturing
   - Commerce (including microenterprises)
   - Tourism

The practical application of the ECLAC methodology has been tested in different Latin American and Caribbean countries, which present a wide range of vulnerability due to their respective sizes, structural and institutional characteristics, and levels of social and economic development [36]. There is some evidence available in literature that indicates that application of the ECLAC methodology has led to improvements in data quality and better, more comprehensive capture of disaster impacts [37].

3.3. Methods used in the United States

The following four broad approaches are utilized in the United States.

3.3.1. Aggregation of human assessor or insurance loss data

The majority of recorded damages and/or losses in the United States as a result of flooding are submitted as claims and assessed by individual assessors for insured property, primarily through the National Flood Insurance Program (NFIP[4]), a public program [38]. This method is highly precise but is not comprehensive, as a result of low flood insurance take up and also low coverage limits (e.g., $250,000 in the NFIP). The method includes the following insurance programs: the NFIP; United States Department of Agriculture (USDA) crop insurance; USDA non-crop insurance, such as Emergency Assistance for Livestock, Honey Bees, and Farm-Raised Fish Program (ELAP); Emergency Forest Restoration Program (EFRP); Livestock Forage Program (LFP); Livestock Indemnity Program (LIP); Noninsured crop disaster Assistance Program (NAP); Supplemental Revenue assistance payments program (SURE); Tree Assistance Program (TAP), and private flood insurance. Similar, but not prepared by insurance programs, the National Oceanic and Atmospheric Administration's (NOAA) Storm Event Database [39] is an estimate of losses compiled, from a variety of sources, by National Weather Service meteorologists.

3.3.2. Model-based methods

A variety of models are used in the United States to assess flood damages and losses, which constitute an essential element of flood risk management by governments and the insurance sector. The primary aim for flood hazard models is to estimate the frequency and intensity of floods, at the same time better understanding of the economic impacts of floods is integral to quantitative flood risk modeling. Characteristics of different types of floods included in this approach can be very different [40].

To undertake flood risk assessments, as well as identify the damage caused by a single flood event, the United States Army Corps of Engineers (USACE) uses two model-based tools: the Hydrologic Engineering Center's (HEC) Flood Impact Analysis (HEC-FIA) and Flood Damage Reduction Analysis (HEC-FDA). The HEC-FIA is a software tool for users to estimate the losses from a single flood event for a user-defined geographic area. Impacts to economic output, such as structural damage, as well as contents, automobile, and agricultural losses, are estimated using a hydrological model. In addition, lost income and expected loss of life are calculated. The program also can be used to inform safety protocols for dam and levee support [41]. The HEC-FDA software, in contrast, calculates the expected annual damages for a given geography and is useful in informing management plans for flood risk [42].

FEMA's Hazus tool applies an engineering flood-depth model to estimate damages from particular flood events. Hazus is designed to produce damage and loss estimates for use by federal, state, regional, and local governments and private enterprises in planning for risk mitigation, emergency preparedness, response, and recovery. The tool can incorporate information about most aspects of the built environment and a wide range of different types of losses. Extensive national databases are embedded within Hazus, containing information such as demographic aspects of the population in a study region, square footage for different occupancies of buildings, and a wide range of different types of adverse impacts. The model performs its analysis at the census block level, with small numbers of buildings. Damage analysis of these small numbers makes Hazus' Flood Model more sensitive to rounding errors [29].

The Hazus model is not widely used to estimate losses, but can be used to estimate *ex-ante* expected losses. It is a deterministic model that contains numerous univariate functions that calculate relative flood losses dependent on the flooding depth. Loss estimates can be obtained for individual objects; however, these values represent average values for a group of similar buildings and are usually aggregated to census blocks. Hazus is mostly used for the residential sector; fewer models are available for other sectors like industry and infrastructure [15]. These models can estimate both *ex-post* losses and the probability and the characteristics of a flood event (*ex-ante*), by taking into account variables such as elevation, watershed characteristics, hydrological factors, bathymetry, and others to estimate inundation location, depth, duration, etc.

3.3.3. Federal budgetary outlays

Programs and policies at the federal level play an important role in both determining the magnitude of flood losses and how these post-compensation losses are financially shouldered across local, state, and federal levels of government, as well as private citizens and businesses. In particular, federal disaster assistance, available after a Presidential disaster declaration, encompasses a variety of programs and policy tools, across multiple agencies, that aim to support state, local, and private entities harmed by a flood. While assistance is often case-specific in its amount and type, these federal budgetary outlays help defray the costs. In addition, provision of post-disaster aid can help with immediate recovery needs such as debris removal and temporary shelter, as well as longer term needs such as property repair [18].

Many federal agencies and departments, state, local, and tribal government agencies receive federal disaster assistance. Various programs include the Congressional appropriations to FEMA through the Disaster Relief Fund (DRF), FEMA's public assistance grant program, and Small Business Administration's (SBA) Disaster Loan Program. In addition, as documented by the Federal Procurement Data System, multiple federal agencies also spend resources on disaster recovery efforts (e.g., Department of Transportation, Department of Defense, Department of Homeland Security, Department of the Interior, Environmental Protection Agency, etc.).

3.3.4. State, tribal, and local government budgetary outlays

A complex spending relationship characterizes disaster assistance in the United States, involving all levels of government from local to state to federal and sometimes tribal. The larger the disaster, the more likely all levels are to participate and spend significant amounts of money. Although major disasters that receive federal declarations get the most attention, state, tribal, and local governments respond to many emergencies on their own, with the first responders generally being from local governments or volunteer organizations using their own personnel and funding. If the disaster, however, exceeds that community's capacity, or if multiple communities are involved, the state steps in to coordinate and add its resources. The funding relationship between the

[4] https://www.fema.gov/national-flood-insurance-program.

federal government and states is highly interdependent. Federal investment in disaster assistance provides states with additional resources that can reduce their costs for federally declared disasters. A state's capacity to respond is one of the factors federal officials consider when determining whether to declare a major disaster and provide federal funds (Pew Charitable Trusts, 2018).

4. Discussion

4.1. Common features in economic evaluation approaches

Major disasters that receive federal declarations get the most attention in Canada, Mexico, and the United States. Overall, the government agencies and private companies of the three countries carry out the assessment of the impact of floods, using different methodologies and on different scales. The level of data availability becomes more restrictive for all methodologies as their application is narrowed to more localized geographic scales.

There are a number of similarities in the flood-costing methodologies between and among the three countries. Common between Canada and the United States is the use of Hazus and its flood model as a method that estimates potential losses from flooding. Parallels can also be drawn between the use of federal budgetary outlays in the United States, and the PBO's methodology for Canada. Both approaches function as economic evaluations undertaken by national government agencies to estimate costs of disaster financial assistance. Further, model-based methods that quantify flood risks and impacts are applied similarly in Canada and the United States. For Canada, both CGE models, that are commonly used by environmental economists, and probabilistic catastrophe models, that are commonly used by insurance industry representatives, depict the economic impacts and risks of flooding. Similarly, for the United States, quantitative modeling of flood risk and costs, whether undertaken by the United States Army Corps of Engineers (USACE) or the insurance industry under the NFIP, attempts to accurately measure and realistically represent the economic impacts of flooding.

The involvement of the insurance industry as holders and users of flood loss data is also a common feature between Canada and the United States. Though overland flood insurance for homeowners has greater availability and uptake in the United States via the NFIP, Canadian insurance-industry organizations are beginning to offer flood risk-based premiums and deductibles as an essential feature of flood insurance programs. The flood-costing methodologies of the United States and Canada have strikingly similar uses and features.

All three countries rely on flood-costing methodologies that account for, or can be modified to consider, broader socio-economic impacts as opposed to operating under purely economic terms of immediate damage costs. Recovery, reconstruction, and replacement costs expressed in dollar or peso amounts seem to be a common function for the various flood-costing methodologies across all three countries as well. The role of federal government agencies as centralized flood-costing data holders and users is clear across all three countries. Each country has national agencies – the PBO and Public Safety Canada for Canada, NOAA, USACE and FEMA for the United States, or CENAPRED for Mexico – that play a key role in measuring the economic impacts of flooding with the goal of preparing and protecting its citizens.

Lastly, knowledge and data gaps are common limitations in the flood-costing methodologies across the three countries. Incomplete information has consequences for the private insurance sector and national government agencies, acting as a barrier for stakeholders to effectively prepare for and respond to the economic impacts of flooding. The similarities in economic evaluation approaches of flooding in Canada, Mexico, and the United States indicate that effective cooperation in measuring flood impacts and responding to disasters among the three countries can be achieved.

4.2. Divergence in economic evaluation methods

The methodologies used in Canada and the United States have a limited scope in terms of the sectors included but are also negatively affected by the availability and accessibility of the data. This situation differs somewhat in the case of Mexico, where data collection is carried out by government agencies through a systematic approach. Subsequently, CENAPRED compiles these data using the ECLAC method to carry out the evaluation of flood impacts in Mexico.

A variety of loss models have been used in the United States, differing in purpose, structure, and regional focus. Loss modeling is often performed separately per sector (i.e. residential, commercial, industrial, agricultural) and at different spatial scales, where the units of analysis vary from individual elements at risk to aggregated land use units. Key differences exist between methods that are aggregation of human assessor loss data and model-based assessment. Human assessor methods are precise, but they are not comprehensive because they only cover insured properties, therefore losses are underestimated. On the other hand, model-based methods are much more comprehensive since they take into account multi variables such as elevation, topography, economic losses, building characteristics, etc., to estimate flood depth, duration, location, and damage to various sectors. These models are still not widely used but they have a greater potential to help federal, state, tribal, and local governments plan risk mitigation, response, and recovery. Accounting for flooding losses in the United States is highly decentralized, leading to a lack of homogenous records and limited data availability. Overall, there is a moderate level of effectiveness and acceptability with how loss data are collected and with their availability and accessibility, which in turn affect their effectiveness in informing methodologies.

Findings from a Pew Charitable Trusts' survey [43] recommends that state and federal policymakers in the United States make collecting comprehensive data a priority. Better data would inform debates about how much each level of government could pay and highlight opportunities to manage growth in overall costs. Ironically, a more complete historical reporting of local flood damage can be found in newspaper archives from cities and towns across the United States [44]. In addition, in their analysis of flood loss data accuracy in the United States, Downton et al. [14] indicate that available records of historical flood damage are inadequate for policy evaluation, scientific analysis, and disaster mitigation planning. Their analysis shows that there are no uniform guidelines for estimating flood losses, and there is no central clearinghouse to collect, evaluate, and report flood damages.

In contrast, data collection in Mexico consists of direct interviews with local agencies for all major disasters. For minor events, information is collected from official sources such Fondo para el Desarrollo Nacional (FONDEN) and Centro Nacional de Comunicación y Operación de Protección Civil (CENACOM). Therefore, the information related to economic impacts of floods is centralized. Access to data for the ECLAC method is dependent, in a significant way, on the historical record of total damages and losses; such current and historic data, together with their respective descriptions, are available in published form on the CENAPRED website.

For the Canadian flood-costing methods, we found that there is a generally acceptable level of data analysis and presentation, whereas availability and accessibility of data borders on inadequate. In most instances, data are presented in a clear and understandable format, but the level of detail required for input to the various methodologies is absent. Overall, there is a moderate level of effectiveness and acceptability with regards to the data that inform these methodologies.

The ways in which the economic impacts of flooding are measured have been suited to the given socio-economic, cultural, environmental, and political conditions of the individual nation. The centralized use of the ECLAC method in Mexico has been effective for disaster assessment. As a unique, holistic, comprehensive, robust, and flexible flood-costing approach, the ECLAC method is unlike any of the economic evaluation approaches of the United States and Canada. The sector-specific nature and careful consideration of losses and additional costs, under the ECLAC method in Mexico, is distinct from the characteristics and uses of flood-costing methods in the United States and Canada. Though it has its limitations, the centralized and standardized use of the ECLAC method in Mexico has resulted in cohesive and organized responses to flooding and other extreme events.

Another key difference in the economic evaluation approaches of flooding among the three countries is the presence of the private insurance sector. Compared to Mexico, the United States and Canada have significantly higher rates of insurance uptake. As a result, it is postulated that there is greater use and importance of private insurance quantitative risk and probabilistic catastrophe models in the United States and Canada. It is worth noting that some of these models and underlying data are proprietary and often not readily accessible to those outside the insurance sector (e.g., academia and governmental agencies).

4.3. Data availability, access and gaps

A key factor in the success or failure of any methodology is the availability of, quality of, and access to data and metadata (such as location/coordinates, areal extent, and time period of the data) needed to undertake an assessment of damages and losses related to a flooding event. The data requirements for each method discussed in Section 3 also vary considerably, depending on the level of comprehensiveness required. The authors for this paper considered each of the methods and subjectively qualified them on the basis the following criteria: data collection (frequency and comprehensiveness), data analysis and presentation, data availability and access, and the overall effectiveness and acceptability in developing estimates of damages and losses. The authors from the three countries – representing diverse academic disciplines and multidisciplinary research areas – utilized a consensus-based approach for application of these criteria in qualitatively determining the robustness of each methodology. We followed established approaches for collecting and presenting expert opinion, such as those used for natural hazard management [45], hydrology [46], and remote sensing [47]. We also duly recognize the limitations of such expert opinion, which might evolve over time or lead to different outcomes in different institutional settings. A broad-brush overview of the robustness of a costing method and its major data-driven challenges is nonetheless useful and useable for further research.

For ease of presentation, this expert opinion is presented through a "traffic light approach," ranging from green (good) to yellow (moderate) to red (poor). Assumptions, uncertainties and gaps in data contribute to the ineffectiveness of the methodologies. Table 1 presents a summary of this expert opinion.

The expert analysis undertaken in Table 1 offers insights about the ingredients for a successful methodology for costing flood event damages and losses. First, the methodologies used in Canada and the United States contain a limited number of sectors, and a lack of data availability and accessibility limits easy implementation. Second, the overlap with the insurance sector means many Canada and United States data are held in proprietary databases and may not be available to the public. Third, the level of data availability becomes more restrictive for all methodologies, as the application is narrowed to small geographic scales. Research shows that there is no national standard for natural disaster damage data collection in the United States [48,49] and that there is no single agency tasked with that effort. In addition, flood loss data are commonly thought to be incomplete and conservative since flood events that do not result in multiple fatalities, high property loss, or media attention, often go unreported, or are, in some cases, inflated through double counting. Mexico's application of the ECLAC method is accompanied by ease of data access; there is also greater confidence in the methodology, because it has been applied in other Latin American countries. Application of the ECLAC method in Canada and the United States may be limited by the comprehensiveness of data available; a trade-off between comprehensiveness and costs of acquiring data may need to be investigated.

4.4. Framework for a shared and comprehensive methodology

As noted at the outset, there is a strong policy argument to assess the damages and losses pertaining to floods in Canada, Mexico, and the United States through a consolidated methodology that connects to the

Table 1
An overview of the flood costing methodologies currently in use in Canada, Mexico and the United States, particularly with respect to data availability and access.

Method	Key Data Holders	Data Collection	Data Analysis & Presentation	Data Availability & Accessibility	Overall Effectiveness & Acceptability
Canadian Methods					
Parliamentary Budgetary Office Method	Federal & provincial agencies; Insurance companies	🔴	🟢	🔴	🟡
Hazus	Default inventory data User-derived data	🔴	🟢	🔴	🟡
Computable General Equilibrium Models	Federal and provincial agencies	🔴	🟢	🔴	🟡
Mexican Method					
ECLAC Method	Local government agencies	🟡	🟢	🟡	🟢
United States Methods					
Human Assessor	Federal government; Insurance companies	🟢	🟢	🟢	🟡
Model-Based Methods	FEMA, US Army Corps of Engineers	🟢	🟡	🟢	🟡
Federal Budget Outlays	Government agencies	🟡	🟡	🟢	🔴
State/Local Budget Outlays	All 50 states, territories & tribal governments	🔴	🔴	🔴	🔴

N·B.: A green light represents complete usefulness and effectiveness in approaches to data; a yellow/amber light represents somewhat usefulness and/or effectiveness; and a red light indicates unacceptability and ineffectiveness.

existing approaches but also fills in information and policy gaps. A consolidated methodology would also address the situation in which no definitive and all-inclusive total loss number is generated by the governments, because no agencies are tasked to do so. The choice of a consolidated methodology would also have ramifications for "vertical" integration of disaster responses in each of the countries. For example, research in the United States shows that states and localities are not comprehensively tracking their disaster spending and the limited data available strongly indicates that these expenditures vary widely [50]. Without complete data on sub-national investments and local cost-sharing practices, any proposal tackling intergovernmental spending issues or cost reduction would be extremely difficult and inaccurate.

In the discussions during the First CEC Expert Workshop, the existing methods used in the three countries were all deemed to have some shortcomings in terms of the inclusiveness and comprehensive coverage of economic impacts across all sectors, as well as expansive assessment of losses over extended periods of time. There was consensus among the workshop participants that the ECLAC method, in use in Mexico, offered the most comprehensive starting point. It was further agreed that this method could be further enhanced to cover key aspects, such as considering incremental emergency services as part of losses. The experts argued that such an approach would minimize the fragmentation of information and disaster-response approaches within the three countries, at various levels of government. It would indeed become a first step in the development of more resilient communities and in evidence-based governmental decision-making.

4.4.1. Key modifications to the ECLAC method

A number of enhancements and modifications to the ECLAC method were recognized and endorsed during the workshop. These modifications are divided into two broad groups.

First, it was agreed to delineate three types of economic impacts, compared to the two used in the ECLAC method [24]: Direct Damages, Indirect Effects, and Losses & Additional Costs. This approach would make the usage consistent with that employed in the insurance sector. The new category of *Indirect Effects* is defined as: second-order effects due to flooding on product, labor, and housing markets. These effects only affect societal welfare if a flood results in a change in market imperfections, e.g. when a housing market in a neighbouring region of the inundated area clears because of a flood [51]. The value of indirect effects is often derived by applying some pre-determined coefficients to direct damages.

Second, a number of sectoral categories included in the ECLAC method were further modified to provide comprehensive inclusion of flood impacts, particularly the social, infrastructure, and transportation sectors. The changes were also in line with the exclusive focus on economic and monetary impacts adopted by the CEC project. The revised list is provided here (key changes shown in italics):

1. Social Sectors:
   - Housing
   - Education
   - Health
   - Water and Sanitation
   - Culture Resources
   - *Local Government and Community*
2. Infrastructure:
   - Transportation
   - Energy and Utilities
   - Technology and Communications
   - Public Infrastructure
3. Economic Sectors:
   - Agriculture Sector (farming, livestock, private forestry)
   - Fisheries
   - Manufacturing
   - Commerce (including microenterprises)
   - Tourism
   - Public Forests
   - Environment
4. Emergency Assistance
   - *Emergency Response*

We briefly summarize here the key modifications and the rationale for those changes. In the 'Social Sectors,' 'Affected populations' and 'Epidemics' are listed as societal, non-monetary impacts of disasters in the ECLAC method; these two elements were eliminated from our proposed methodology not because of lack of their significance, but rather due to their inherent non-monetary nature. The experts proposed that water and sanitation, because of their critical link with social wellbeing and as a human right declared by the United Nations [52], fit better under the Social Sectors instead of 'infrastructure.' 'Culture and cultural assets' was re-labeled to 'Cultural Resources' to be more inclusive, particularly to incorporate diverse perspectives such as those of Indigenous communities. A new entry of 'Local Government and Community' was added to the Social Sectors incorporating infrastructure and services that fall under the local government/municipality. This entry is meant to account for loss of tax revenue, unemployment increases, costs of recovery, and revenue loss to a community and/or municipality – items that are not captured by other entries in this category.

In the 'Infrastructure' category, 'Power Sector' was redefined as 'Energy and Utilities,' with the understanding that such a modification would allow the inclusion of natural gas supply lines and distribution mechanisms which are not included in the ECLAC method. A new entry of 'Technology and Communication' was also incorporated into the infrastructure category to include communication-related technological elements such as Internet cables, cellular phone signal transmission systems, and telephonic communications infrastructure. Indirect effects may include the loss of revenue to businesses as a result of affected telecommunication services. Another new entry is 'Public Infrastructure' that is meant to include non-market value of public spaces that might become unavailable due to flooding; losses and additional costs may include those related to re-scheduling public events.

In the 'Economic Sectors,' 'fisheries' as a sector is separated out from the 'Agriculture Sector,' with the understanding that the nature of impacts on fisheries is significantly different from the farming- and ranching-related entries in the Agriculture Sector. Similarly, 'Public Forests' was also separated out from the Agriculture Sector, to capture forestry activities on publicly owned lands as distinct from that privately owned. A new entry of 'Environment' is also included as an Economic Sector; the flood-related impacts on the environment include erosion and sedimentation, impact on the health of wildlife and aquatic species, distribution of nutrients and pollutants in different ecosystems, and impacts on landscapes. The experts at the workshop recognized that current knowledge level of the economic significance of these environmental impacts is not well understood or quantified. Nonetheless, recognizing their economic significance is a first step in addressing data and knowledge deficits.

We also propose adding a new category of 'Emergency Assistance' in our method. The purpose of this category is to adequately capture losses and additional costs triggered as a result of governmental response to flooding. These costs could include those related to transportation of patients/wounded, equipment mobilization to address emergency responses, building of temporary shelters for those displaced due to flooding, and other search-and-rescue missions needed to locate any missing persons. There has been some experience of calculating these costs in Mexico, under the aegis of CENAPRED, with successful quantification of the monetary aspects of these incremental emergency responses [25].

4.4.2. The proposed consolidated methodology

The proposed consolidated methodology is presented in Table 2; it

Table 2
The proposed consolidated methodology for application in the CEC countries, Canada, Mexico and the United States.

Category	Direct Damages	Indirect Effects	Losses & Additional Costs
Social Sectors			
Housing	*Household items.* Cost of the total or partial destruction of furniture, electric appliance, sanitary facility, and other equipment. *Dwelling.* Cost of the total or partial destruction of dwellings or properties. *Cleaning.* Cost of cleanup and mud removal. Total or irreversible structural damage, in which case all the costs of demolition and rubble removal.	*House rental.* Rent increases due to the housing shortage.	*Temporary accommodation.* Costs of the provision of temporary accommodation for persons whose homes were destroyed or had to be abandoned. *Relocation.* Cost of migration and permanent relocation of communities.
Education	*Building.* Cost of the total or partial destruction of buildings. *Classroom.* Cost of the total or partial destruction of classrooms, also included furnishings, tables, cupboards, desk and chairs, and textbooks. *Cleaning.* Cost of cleanup and mud removal. Total or irreversible structural damage, in which case all the costs of demolition and rubble removal.	*Missing workdays* due to school closure.	*Temporary classroom.* Rental of mobile classrooms. Reset service. Outlays needed to restore the education service.
Health	*Death toll.* Count of people died directly by the flood event. *Physical damage.* Damage to physical infrastructure can involve structural elements (beams, pillars, structural flooring, load-bearing walls, foundations, etc.) as well as non-structural or architectural elements (partitions, doors, windows, non-structural roofing and floors, interior and exterior walls, perimeter fences and so forth). *Medical equipment.* Cost of the losses of vital service connections or medical equipment (e.g. water, electricity, gas, oxygen).	*Patient.* Increase the number of patients in the emergency room *Workdays lost.* Missing workdays due to psychological impacts, stress, and anxiety (or PTSD).	*Post-disaster epidemic.* Cost of actions not planned prior to the disaster. *Hospital-related costs.* Additional services to account for the increase of health issues/costs of treating diseases (i.e. respiratory disease) as a result of flooding *Structure-related costs.* Cost of post-disaster health concerns, such as removal of black mold
Water and Sanitation	*Storage tank.* Cost of the total or partial destruction of storage tanks. *Distribution network/treatment plant.* Cost of the total or partial destruction of distribution network treatment plants. *Rebuilding.* Cost of rebuilding water infrastructure and reconstruction of dams and levees.		*Temporary water needs.* Reduction in sales of water. Use of tanker trucks, trailers, or makeshift carriers to distribute water.
Cultural Resources	*Place of worship.* Cost of the total or partial destruction of places of worship. *Recreation area.* Cost of the total or partial destruction of recreation areas. *Sacred burial place.* Cost of the total or partial destruction of sacred burial places. *Cultural artifact.* Cost of the total or partial destruction of cultural artifacts (e.g., building) in landscapes. *Museum collection.* Cost of the total or partial destruction of museum collections and artifacts in buildings. *Culturally-relevant historic structure.* Cost of the total or partial destruction of non-market value (as in public infrastructure). *Damaged zone.* Cost of the total or partial destruction of zones.		*Revenue* (cultural resources) Loss of revenue to religious/cultural organizations. *Recreation.* Loss of recreation services (non-market values).
Local Government/ Community	*Local infrastructure and services.* Cost of the damages of local infrastructure and services provided by the local government/municipality.	*Workdays lost.* Unemployment increases.	*Revenue.* Loss of tax revenue *Loans and bonds.* Cost to recover (taking out loans and bonds). *GDP.* Loss of Gross Domestic Product (GDP) to municipalities
Infrastructure			
Transportation	*Railroad.* Cost of the total or partial destruction of railroads. *Airport.* Cost of the total or partial destruction of airports. *Port.* Cost of the total or partial destruction of ports. *Road.* Cost of the total or partial destruction of roads and highways.	*Revenue* (port). Loss of revenue at ports.	*Cost for transporting freight.* Partial or total road closures imply greater distances and longer travel times for users, as well as higher vehicle operating costs. *Loss of tolls* Cost for passengers Partial or total road closures imply greater distances and longer travel times for users, as well as higher vehicle operating costs. *Additional costs for crews.* Additional costs associated with the deployment and mobilization of crews for damage repair

(*continued on next page*)

Table 2 (*continued*)

Category	Direct Damages	Indirect Effects	Losses & Additional Costs
	Protection wall/dyke. Cost of constructing protection walls and dykes for roads and highways. *Restore the infrastructure*. Cost of the work needed to restore the infrastructure to pre-disaster conditions. *Restore the services*. The rehabilitation works required to restore service (i.e. to make a road accessible and passable), as well as the replacement works needed to return the infrastructure to its original state.		
Energy & Utilities	*Power generation plant.* Cost of the total or partial destruction of power generation plants. *Substation.* Cost of the total or partial destruction of substations of electricity and natural gas. *Transmission line and distribution grid*. Cost of the total or partial destruction of transmission lines, gas pipelines, and distribution grids. *Dispatch center*. Cost of the total or partial destruction of dispatch centers of electricity and natural gas.	*Spills damage*. Environmental damage caused by spills.	*Revenue* forgone by electric power utilities during the period of disruption. *Rehabilitation/reconstruction.* Cost of supplying power needs temporarily during rehabilitation and reconstruction of the installations affected
Technology & Communications	*Service tower*. Cost of the total or partial destruction of service towers. *Communication infrastructure*. Cost of the total or partial destruction of communication infrastructure.	*Revenue (manufacturing)*. Loss of revenue from manufacturing due to a lack of communication services. *Revenue (commerce)*. Loss of revenue from commerce due to a lack of communication services.	
Public infrastructure		*Non-market value* of public space	*Cleaning*. Involved in cleanup and mud removal *Rescheduling* public events' costs
Economic Sectors			
Agriculture	*Road or bridge.* Cost of the total or partial destruction of roads or bridges within the farm property. *Storage space.* Cost of the total or partial destruction of buildings and installations for the storage of equipment. *Infrastructure used in farming.* Cost of the total or partial destruction of infrastructure used in farming. *Infrastructure used in livestock.* Cost of the total or partial destruction of infrastructure used in livestock. *Infrastructure used in poultry*. Cost of the total or partial destruction of infrastructure used in poultry. *Infrastructure used in private forestry activity.* Cost of the total or partial destruction of infrastructure used in private forestry activities.		*Market value of crop.* Lower yields than normal for the crops. *Income*. Lesser harvest production means lower incomes for producers. *Market value of livestock*. Reduction in physical productivity or lower yields than normal for the species of livestock. *Market value of poultry*. Reduction in physical productivity or lower yields than normal for the species of poultry. *Market value of private forest product* Lower yields than normal for private forest products.
Fisheries	*Storage space*. Cost of constructing tanks, cages, and other installations for the cultivation of fish and crustaceans. Silos, stalls, corrals, troughs, and pens for raising fish or crustaceans.		*Market value of fish*. Reduction in physical productivity or lower yields than normal for fish. *Market value of crustaceans*. Reduction in physical productivity or lower yields than normal for crustaceans. *Income*. Lesser harvest production means lower incomes for producers.
Manufacturing	*Building and facility*. Cost of the total or partial destruction of buildings, facilities and furniture. *Machinery and equipment.* Cost of the total or partial destruction of machinery and equipment. *Inventory of goods.* Cost of the total or partial destruction of inventories of goods being processed, finished goods, raw materials and spare parts.	*R&D impacts.* Loss of R&D prototypes, documentation, software Loss of wages, including temporary jobs, of workers due to shutting down of manufacturing facilities.	
Commerce	*Building and facility*. Cost of the total or partial destruction of buildings, facilities and furniture. *Machinery and equipment.* Cost of the total or partial destruction of machinery and equipment. *Inventory of goods.* Cost of the total or partial destruction of inventories of goods being processed, finished goods, raw materials and spare parts.	*Credit.* Decreased credit scores and bond downgrades for businesses.	
Tourism	*Tourism area*. Cost of the total or partial destruction of tourism areas.	Loss of wages, including temporary jobs, of workers in the tourism sector.	*Service flow*. Damage sustained by tourism establishments located in a disaster area will have a negative impact on the provision of service flows.

(*continued on next page*)

Table 2 (*continued*)

Category	Direct Damages	Indirect Effects	Losses & Additional Costs
	Property. Cost of the total or partial destruction of properties.		
Public Forest	*Employee*. The number of people whose activities rely on forests in the area affected. *Road or bridge*. Cost of the total or partial destruction of roads or bridges in parks. *Infrastructure used in the park*. Cost of the total or partial destruction of Infrastructure used in parks.	*Workday lost*. Cost of people unable to work.	*Market value*. The types of forest products and the quantity in a given period.
Environment	*Erosion and sedimentation.* Cost of the damages of erosion and sedimentation. *Wildlife and aquatic species health.* Cost of the damages of wildlife and aquatic species. *Dispersal of nutrients and pollutants.* Floodwater can contain debris (e.g., trees, stones, and pieces of houses) and pollutants (e.g., pesticides). Sedimentation and turbidity can give rise to algae and aquatic plant growth that jeopardize water quality. *Local landscapes and habitats.* Cost of the damages of local landscapes and habitats.		
Emergency Assistance			
Emergency Response			*Transporting the wounded or other emergency evacuations.* The additional cost of emergency transportation by land or through air. *Equipment.* The rent or purchase of equipment used for emergency care work. *Temporary shelters.* The installation of temporary shelters *Search for people.* Costs generated by the search and rescue operations for people.

incorporates the changes listed in Section 4.4.2 and provides details of how the economic impacts of flooding are captured for various sectors. The CEC project is in the process of populating a database designed in accordance with Table 2. Detailed analysis of data from Canada, Mexico, and the United States is being undertaken to assess the relative magnitude of economic impacts of flooding not being captured in the approaches used currently; that research work will be the subject of future publications and is beyond the scope of this paper.

5. Conclusions

5.1. Key findings

The assessment of existing literature and the expert dialogue in the workshop points to a number of challenges related to data availability, access, quality, and spatial coverage. The experts participating in the workshop pointed out that reliance on existing databases will likely be insufficient to provide a comprehensive and inclusive picture, considering there are spatial, temporal, and sectoral gaps. If Table 2 is used as a benchmark for the information needed to make a comprehensive and credible assessment of flood-related costs, then it is likely that Mexico's databases would yield information that has the closest match to our proposed methodology. That is not surprising considering that Table 2 is derived from a costing method currently in use in Mexico.

It is foreseeable that a range of methods may need to be invoked, at least initially, to fill the data gaps encountered while populating a database presented in Table 2. For example, we recognize that obtaining data on payouts and take-up rates from insurance companies can be a difficult process, as this information is often proprietary and confidential. The experts gathered at the workshop opined that it would, therefore, be critical to distinguish between *ex post* data available from different sources versus estimates generated through various models (such as hazus or CGE simulations). Similarly, ensuring comparable quality of data from different sources could be challenging as well. In the long run, it can be envisioned that monitoring and data collection in the three countries can be modified such that those data become readily available and reliance on mathematical models is minimized or eliminated.

The usefulness of the methodology proposed in this paper eventually lies with its utility to various stakeholders, including the insurance industry, businesses, government agencies, academia, and Indigenous organizations. Inclusion of representatives and perspectives from these stakeholders, as was the case for the First CEC Expert Workshop, is an effective way of ensuring that the outputs generated from this methodology are useable and useful.

5.2. Recommendations and future research

Discussions during the First CEC Expert Workshop and deliberations among the CEC project team members has led to identification of a number of areas in which further research and information generation is needed. Equally, we have identified some recommendations in how to achieve a comprehensive picture of flood-related damages, indirect effects, losses, and additional costs. These recommendations are briefly presented here.

Although there are clear benefits to establishing a shared methodology deployed across the three countries, challenges to its implementation remain. Political leadership, high-level officials from all levels of government, and multiple agencies must agree to gathering data and metadata accurately and then to create a framework or information warehouse to share those data in a timely fashion. This level of coordination requires planning and allocation of both financial and human resources. To be successful in this endeavor, a shared database, with proper security, data quality checks, easy-to-use interface, etc., will need to be designed, developed, tested, and implemented, with appropriate training across multiple agencies and jurisdictions.

In view of increasing levels of threats from flooding, there needs to be a commitment from policymakers at the state/province and federal levels to collect and share comprehensive data. As discussed in the previous section, such incremental investment into data gathering and maintaining an information warehouse for its dissemination is critical to ensure that timely, comprehensive, and inclusive data and corresponding pertinent information are available to both policy makers and the at-risk general public; we anticipate that establishment of any such information warehouse might be subject to tri-national governmental negotiations and intense public scrutiny. Vigorous policy debates, based on findings from our proposed methodology, can help draw a contrast between benefits of community-level resilience-building through investments into infrastructure and better preparedness approaches, and the total costs a community accrues due to flooding. Such debates around trade-offs between short-term gains and long-term protection can help set priorities at community- and national-levels.

The CEC project is aiming to pilot-test the database based on Table 2 for a five-year window (2013–2017), as per the project details approved by the three federal governments. This window of time is sufficient in duration to discern some regional and temporal trends about where the flooding is occurring, and when and how worst economic impacts take place. There is, however, an argument for extending this window in time to a ten-year period (say, 2007–2017), particularly to better analyze the temporal trends. Such an extended approach, although beyond the scope of the current project, would better evaluate the applicability and robustness of our proposed methodology.

The notion of what constitutes an "extreme flood" was discussed at the First CEC Expert Workshop, but a clear consensus did not emerge. Such a definition has important consequences for mobilization of resources and support at national or subnational levels. We discussed that extremeness can be defined by the natural environment (e.g., amount of precipitation over a certain time period, flood return period, etc), societal factors (e.g., number of people impacted), economic impacts (e.g., magnitude of damages and losses), or a combination of all of them. Developing a definition for extreme flooding, including identification of hydrological, societal and economic thresholds, will require further research and examination of published literature as well as detailed dialogue with government agencies to achieve a consensus.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work is the product of cooperation of many experts in key institutions in Canada, Mexico and the United States. We thank the Commission for Environmental Cooperation (CEC) for project funding and for its assistance in administration, coordination and organization of the work.

List of Abbreviations Used in the Paper

CDD	Canadian Disaster Database
CEC	Commission for Environmental Cooperation
CENACOM	Centro Nacional de Comunicación y Operación de Protección Civil
CENAPRED	Centro Nacional de Prevención de Desastres
CGE	Computable General Equilibrium
DFAA	Disaster Financial Assistance Arrangements
DRF	Disaster Relief Fund
ECLAC	Economic Commission for Latin America and the Caribbean
EFRP	Emergency Forest Restoration Program
ELAP	Emergency Assistance for Livestock, Honey Bees, and Farm-Raised Fish Program
ENSO	El Niño–Southern Oscillation
FEMA	Federal Emergency Management Agency
FONDEN	Fondo para el Desarrollo Nacional
GIS	Geographic Information System
HEC-FIA	Hydrologic Engineering Center's Flood Impact Analysis
HEC-FDA	Hydrologic Engineering Center's Flood Damage Reduction Analysis
IBC	Insurance Bureau of Canada
IPCC	Intergovernmental Panel on Climate Change
LFP	Livestock Forage Program
LIP	Livestock Indemnity Program
NAP	Noninsured crop disaster Assistance Program
NFIP	National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PBO	Parliamentary Budget Officer
RMS	Risk Management Solutions Inc.
SBA	Small Business Administration
SURE	Supplemental Revenue Assistance Program
TAP	Tree Assistance Program
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture

References

[1] T.C. Peterson, R.R. Heim, R. Hirsch, D.P. Kaiser, H. Brooks, N.S. Diffenbaugh, D. Wuebbles, Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: state of knowledge, Bull. Am. Meteorol. Soc. 94 (6) (2013) 821–834.

[2] V. Fernández, R. Silva, E. Mendoza, B. Riedel, Coastal flood assessment due to extreme events at Ensenada, Baja California, Mexico, Ocean Coast Manag. 165 (2018) 319–333.

[3] L. Bakkensen, L. Blair, Flood damage assessments: theory and evidence from the United States. Oxford Research Encyclopedia of Politics, Oxford University Press, Oxford, United Kingdom, 2020.

[4] IPCC, in: C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M. D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, P.M. Midgley (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of the Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom, 2012.

[5] S.I. Seneviratne, N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, X. Zhang, Changes in climate extremes and their impacts on the natural physical environment, in: V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M. D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, P.M. Midgley (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 2012, pp. 109–230. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC).

[6] G.A. Hodgkins, P.H. Whitfield, D.H. Burn, J. Hannaford, B. Renard, K. Stahl, D. Wilson, Climate-driven variability in the occurrence of major floods across North America and Europe, J. Hydrol. 552 (2017) 704–717.

[7] A.W. Sturdivant, R.D. Lacewell, Estimated Benefits of IBWC Rio Grande Flood-Control Projects in the United States. Contract Report provided to the International Boundary and Water Commission (IBWC). TR-275, Texas Water Resources Institute, College Station, TX, 2004. Retrieved on 14 August 2020 from: https://oaktrust.library.tamu.edu/handle/1969.1/6103. September 2004.

[8] A.O. Pinson, S.K. Scissons, S.W. Brown, D.E. Walther, Post Flood Report: Record Rainfall and Flooding Events during September 2013 in New Mexico, Southeastern Colorado and Far West Texas, 2014. Retrieved on 14 August 2020 from: https://edac.unm.edu/projects/floodImages/2013%20September%20Flood%20Report%20FINAL.pdf.

[9] R.W. Sandford, D. Harford, J. O'Riordan, The Columbia River Treaty – A Primer, Rocky Mountain Books, Toronto, Canada, 2014.

[10] B. Cosens, The Columbia River Treaty: an opportunity for modernization of basin governance. 27 *Colo, Nat. Resources, Energy & Envtl. L.* Rev. 27 (2016), https://doi.org/10.1080/15481603.2019.1587890.

[11] USACE, Columbia River Treaty – History and 2014/2024 Review. Bonneville Power Administration and the U.S. Army Corps of Engineers, 2014. Retrieved on 14 August 2020 from: https://www.bpa.gov/news/pubs/GeneralPublications/crt-Columbia-River-Treaty-History-and-2014-2024-Review.pdf.

[12] M. Allaire, Socio-economic impacts of flooding: a review of the empirical literature, Water Security 3 (2018) 18–26.

[13] CENAPRED, Características del impacto socioeconómico de los principales desastres ocurridos en México en el período 1980-1991. Coordinación de Investigación. Área de Estudios Económicos y Sociales, CENAPRED, 2001.

[14] M. Downton, R.A. Pielke, How accurate are disaster loss data? The case of US flood damage, Nat. Hazards 35 (2005) 211–228.

[15] A.B. Smith, R.W. Katz, US billion-dollar weather and climate disasters: data sources, trends, accuracy and biases, Nat. Hazards 67 (2013) 387–410.

[16] H. McGrath, E. Stefanakis, M. Nastev, Sensitivity analysis of flood damage estimates: a case study in Fredericton, New Brunswick, International Journal of Disaster Risk Reduction 14 (2015) 379–387.
[17] J.B. Davies, Economic analysis of the costs of flooding, Can. Water Resour. J./ Revue canadienne des ressources hydriques 41 (1–2) (2016) 204–219.
[18] Congressional Budget Office, Expected Cost of Damage from Hurricane Winds and Storm-Related Flooding, Congress of the United States, 2019.
[19] FEMA, Multi-Hazard Identification and Risk Assessment: A Cornerstone of the National Mitigation Strategy, Mitigation Directorate, Washington, DC, 1997, 200913.
[20] Public Safety Canada, Guidelines for the Disaster Financial Assistance Arrangements, 2008. ISBN No. 978-0-662-47287-2 Cat. No. : PS4-52/2007E.
[21] A.A. Sadiq, J. Tyler, D.S. Noonan, A review of community flood risk management studies in the United States, International Journal of Disaster Risk Reduction 41 (2019) 101327.
[22] B. Merz, H. Kreibich, R. Schwarze, A. Thieken, Assessment of economic flood damage, Nat. Hazards Earth Syst. Sci. 10 (1) (2010) 697–1724.
[23] A.K. Pistrika, Flood damage estimation based on flood simulation scenarios and a GIS platform, European Water 30 (2010) 3–11.
[24] ECLAC (Economic Commission for Latin America and the Caribbean), Manual para la evaluación del impacto socioeconómico y ambiental de los desastres (versión final) (LC/MEX/G.5; LC/L.1874), Mexico City, ECLAC subregional headquarters in Mexico, 2004.
[25] CENAPRED, Características del impacto socioeconómico de los principales desastres ocurridos en México del año 2004. Coordinación de Investigación. Área de Estudios Económicos y Sociales, CENAPRED, 2004.
[26] CENAPRED, Desastres en México: impacto social y económico. Subdirección de Estudios Económicos y Sociales, CENAPRED, 2019.
[27] Office of the Parliamentary Budget Officer, Estimate of the Average Annual Cost of Disaster Financial Assistance Arrangements Due to Weather Events, 2016 [Report]. Retrieved on 22 May 2020 from, https://www.pbo-dpb.gc.ca/web/default/files/Documents/Reports/2016/DFAA/DFAA_EN.pdf.
[28] FEMA, Hazus Flood Model, 2019. Retrieved on 22 May 2020 from, https://www.fema.gov/hazus-mh-flood-model.
[29] FEMA, Hazus Flood Model User Guidance, 2018. Retrieved on 22 May 2020 from, https://www.fema.gov/media-library-data/1564766454464-d77d2c219be0f5431 5aa79ac5dbc3547/Hazus_4-2_Flood_User_Manual_August_2019.pdf.
[30] N.L. Hastings, C.L. Wagner, W. Chow, C.F. Sidwell, R.A.L. White, Hazus-MH 2.1 Canada User and Technical Manual: Flood Module, Geological Survey of Canada, 2017. Open File 7940, 143. Retrieved on 01 August 2020 from, http://oaresource.library.carleton.ca/wcl/2017/20171205/M183-2-7940-eng.pdf.
[31] M. Nastev, N. Todorov, Hazus: a standardized methodology for flood risk assessment in Canada, Can. Water Resour. J. 38 (3) (2013) 223–231.
[32] H. Mcgrath, E. Stefanakis, M. Mccarthy, M. Nastev, Data preparation for validation study of hazus Canada flood model, in: 10th Annual Conference of the International Institute for Infrastructure Renewal and Reconstruction, 2014.
[33] B.H. Mitra-Kahn, Debunking the Myths of Computable General Equilibrium Models, Schwartz Center for Economic Policy Analysis and Department of Economics, 2008. The New School for Social Research, Working Paper Series. Retrieved on 22 May 2020 from, http://www.economicpolicyresearch.org/images/docs/research/economic_growth/SCEPA%20Working%20Paper%202008-1_Kahn.pdf.
[34] L. Carrera, G. Standardi, F. Bosello, J. Mysiak, Assessing direct and indirect economic impacts of a flood event through the integration of spatial and computable general equilibrium modelling, Environ. Model. Software 63 (2015) 109–122.
[35] A.B. Gertz, J.B. Davies, A CGE Framework for Modelling the Economics of Flooding and Recovery in a Major Urban Area, Economic Policy Research Institute, 2015. EPRI Working Papers. London, ON: Department of Economics, University of Western Ontario. Retrieved on 22 May 2020 from, https://ir.lib.uwo.ca/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=1075&context=economicsepri_wp.
[36] D. Bitrán, S. Santa Cruz, R. Meli, El Impacto de los Desastres Naturales en el Desarrollo: Documento Metodológico Básico para Estudios Nacionales de Caso, 2005. LC/MEX/L.694. Español.
[37] R. Zapata, B. Madrigal, Economic impact of disasters: evidence from DALA assessments by ECLAC in Latin America and the Caribbean, Estudios y perspectivas 117 (LC/MEX/L.941, 2009 (Mexico City, ECLAC subregional headquarters in Mexico).
[38] R.O. King, National Flood Insurance Program: Background, Challenges, and Financial Status, Congressional Research Service, 2011. CRS Report for Congress. Retrieved on 22 May 2020 from, https://pdfs.semanticscholar.org/72e5/45bd699c19cf896876f604413c0a3fa687ea.pdf.
[39] National Oceanic and Atmospheric Administration, Storm Events Database, 2019. Retrieved from, https://www.ncdc.noaa.gov/stormevents/.
[40] Verisk, Retrieved on 22 May 2020 from, https://www.verisk.com/insurance/products/property-claim-services/estimates-of-insured-property-loss/, 2019.
[41] USACE, HEC-FIA. Flood impact analysis. User's manual, Retrieved on 22 May 2020 from, https://www.hec.usace.army.mil/software/hec-fia/documentation/HEC-FIA_30_Users_Manual.pdf, 2015.
[42] USACE, HEC-FDA. Flood Damage Reduction Analysis. User's Manual, 2016. Retrieved on 22 May 2020 from, https://www.hec.usace.army.mil/software/hec-fda/documentation/CPD-72_V1.4.1.pdf.
[43] Pew Charitable Trusts, Federal disaster assistance goes beyond FEMA, Retrieved on 22 May 2020 from, http://www.pewtrusts.org/en/research-and-analysis/fact-sheets/2017/09/federal-disaster-assistance-goes-beyond-fema, 2017.
[44] M. Downton, J.Z. Barnard Miller, R.A. Peilke, Reanalysis of U.S. National weather service flood loss database, Nat. Hazards 6 (1) (2005) 13–22.
[45] S. Scheuer, D. Haase, Operationalizing Expert Knowledge and Stakeholder Preferences in Integrated Natural Hazard Risk Assessment. International Congress on Environmental Modelling and Software, vol. 6, 2012. Leipzig, Germany, July 2012. Retrieved on 14 August 2020 from: https://scholarsarchive.byu.edu/iemssconference/2012/Stream-B/6.
[46] M. Antonetti, M. Zappa, How can expert knowledge increase the realism of conceptual hydrological models? A case study based on the concept of dominant runoff process in the Swiss Pre-Alps, Hydrological Earth System Science 22 (2018) 4425–4447.
[47] D.A. Arvor, B. Mariana, F. Zoe, M. Isabelle, D. Laurent, Ontologies to interpret remote sensing images: why do we need them? GIScience Remote Sens. 56 (6) (2019).
[48] National Weather Service (NWS), United States Flood Loss Report - Water Year 2014, Hydrologic Information Center - NWS Annual Flood Loss Summary Reports To U.S. Army Corps of Engineers, 2015.
[49] L.A. Bakkensen, X. Shi, B.D. Zurita, The impact of disaster data on estimating damage determinants and climate costs, Economics of Disasters and Climate Change 2 (2017) 49–71.
[50] Pew Charitable Trusts, What we don't know about state spending on natural disasters could cost us, Retrieved on 22 May 2020 from, https://www.pewtrusts.org/en/research-and-analysis/reports/2018/06/19/what-we-dont-know-about-state-spending-on-natural-disasters-could-cost-us, 2018.
[51] W. Jonkhoff, Flood risk assessment and policy in The Netherlands, in: OECD (2009), Green Cities New Approaches to Confronting Climate Change, OECD Workshop Proceedings, Las Palmas De Gran Canaria, Spain, 2009. Retrieved on 22 May 2020 from: http://www.oecd.org/regional/regional-policy/45377963.pdf#page=220.
[52] United Nations (UN), The Human Right to Water and Sanitation. UN General Assembly Resolution A/RES/64/292, 2010. Retrieved on 22 May 2020 from: https://undocs.org/en/A/RES/64/292.